New Millennium Program ST6: Autonomous Technologies for Future NASA Spacecraft

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ABSTRACT

The purpose of NASA's New Millennium Program (NMP) is to validate advanced technologies in space and thus lower the risk for the first mission user. The focus of NMP is only on those technologies which need space environment for proper validation. The ST6 project has developed two advanced, experimental technologies for use on spacecraft of the future. These technologies are the Autonomous Sciencecraft Experiment and the Inertial Stellar Compass. These technologies will improve spacecraft's ability to:

- make decisions on what information to gather and send back to the ground
- determine its own attitude and adjust its pointing

The significance of these technologies is in making the space missions less dependent on operators on the ground and shifting the decision making to the spacecraft itself. Autonomous pointing and science gathering will also allow the spacecraft to react to ephemeral events that otherwise could not be detected in time due to long communication times from deep space.

Autonomous sciencecraft technology involves feature and change detection, continuous planning technology, and robust execution. It is equipped with software that checks spacecraft performance and has resources to prevent errors. Several algorithms are used to analyze remote sensing imagery onboard to detect the occurrence of science events. These algorithms will be used to downlink science data only on change, and will detect features of scientific interest such as volcanic eruptions, flooding, ice breakup, and presence of cloud cover. The results of these onboard science algorithms are inputs to onboard planning software that then modify the spacecraft observation plan to capture high value science events. This new observation plan is then executed by a robust goal and task oriented execution system, able to adjust the plan to succeed despite run-time anomalies and uncertainties.

The Inertial Stellar Compass (ISC) will enable a spacecraft to continuously determine its attitude and recover its orientation after a temporary malfunction or power loss. This is done by the integration of a miniaturized star camera and gyro system. Compass technology uses an active pixel sensor (APS) in a star-tracking camera and a three-axis system of microelectromechanical (MEMS) gyros.

These technologies will add autonomy to the future NASA spacecraft and allow mission resources to focus on science goals.

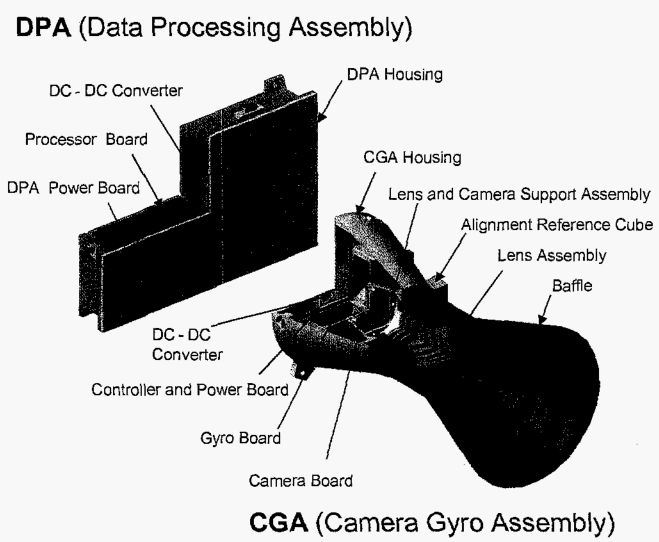
1. INERTIAL STELLAR COMPASS TECHNOLOGY

The ISC is an innovative attitude determination sensor that combines MEMS and APS technologies in an integrated package to produce a real-time, robust attitude solution and rate estimate. Among the key advantages of the ISC are its low power, ease of integration with a host spacecraft, and ability to maintain better than 0.1° accuracy during high rate (up to 40°/s) maneuvers. Key ISC performance features include:

- Better than 0.1° (1-sigma) accuracy in each axis
- High-rate maneuver capability (up to 40°/s)
- Self-initialization (over 99% of the sky)
- Low Mass ~ 2.9 kg
- Low Power ~ 3.5 W

The ISC program is nearing the conclusion of the ground validation phase. The instrument has been extensively tested and has demonstrated promising results. The instrument will be integrated with its carrier spacecraft in mid-2005 and tested in space in 2005-2006 time frame.

Figure 1 ISC cutout view



The ISC consists of two separate units as shown in Figure 1, connected by a cable: the Camera Gyro Assembly (CGA), which contains the sensors, and the Data Processing Assembly (DPA) containing the sensor's embedded computer and power supply electronics. The CGA collects raw sensor data upon command and returns the data to the DPA for processing. The CGA provides a simple serial interface to the DPA (or any other flight computer) and directs all necessary timing and control needed by the star camera and MEMS gyros.

The CGA includes the optics, mission specific light baffle, focal plane array, three MEMS single-axis gyros with analog-to-digital conversion electronics, an interface board, and a 28V, triple output, DC/DC converter. The heart of the star camera is a STAR250 512x512 active pixel sensor array from Fill Factory with an on-chip 10-bit A/D converter. The camera has a command-ready interface to support windowing, various integration times, selectable frame count, and built-in test. The 21° square FOV star camera optics are based on a commercial 35 mm, f/1.2 lens manufactured by Zeiss and modified for space flight applications. Besides the camera subsystem, the CGA houses the gyro subsystem which contains three single-axis MEMS gyros for sensing angular rate. The tiny gyro sensors are etched in silicon using a Charles Stark Draper Laboratory (CSDL) - developed MEMS process. A sense mass is driven into oscillation by electrostatic motors. The mass oscillates in one axis and as the body is rotated, the Coriolis effect causes the sense mass to oscillate out of plane. This change is measured by capacitive plates and is proportional to the rotational rate of the body. The CGA is 16 cm high (without mission specific baffle), approximately 17 cm wide at its circular base, weighs 1.3 kg and consumes 2 W of power.

The DPA contains an Atmel ERC32 processor, power supply electronics (PSE), and a 28V, single output, DC/DC converter made by Modular Devices Inc. The DPA interfaces to a host spacecraft via a 3-wire, bi-directional, asynchronous RS422 serial port. Input rates are 9600 baud with a variable output data rate to 38.4K baud. The large downlink capability of the ISC can support transmission of raw imagery from the star camera in addition to the transfer of highly sampled raw and compensated gyro data from the gyro electronics. All of the embedded software necessary for ISC operation runs internal to the DPA. The DPA dimensions are 15 cm x 23 cm x 4 cm. It weighs 1.6 kg and consumes 1.5 W.

The two-unit design facilitates a simple integration with a host spacecraft. Only the CGA needs to be precisely aligned with the host spacecraft using the reference cube located on the CGA housing. The modular design was emphasized for operability by allowing concurrent development and testing of the two units. In addition, the modular design suits interesting future applications and variations of the ISC. [1]

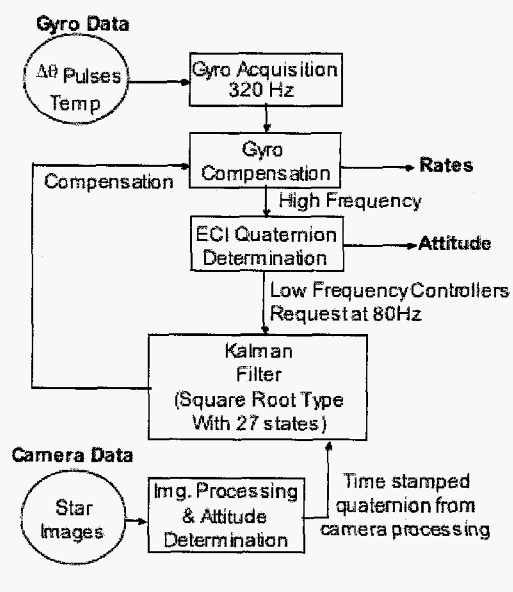


Figure 2 ISC data flow

A simple system data flow is described in Figure 2. During operation, attitude information is propagated by the ISC's MEMS gyros. The gyros sense inertial rates that are sampled at a high frequency (320 Hz). The raw gyro data is compensated and processed through a Kalman filter to produce the attitude quaternion, which is transmitted to the host spacecraft in real time, at a frequency of 5 Hz. The star camera is used periodically (every few minutes) to obtain a camera quaternion that enables the gyro errors to be removed and the inherent drift of the gyros to be calibrated and compensated. Stars in the image are identified using a lost-in-space (LIS) attitude determination algorithm that analyzes the image against a stored star catalog to help identify the camera's orientation without any prior knowledge of the spacecraft's attitude. [2] Once initialized, the gyros are used to maintain attitude knowledge continuously until the next stellar update can be obtained to support gyro compensation. The complementary use of the gyros and camera data help the spacecraft overcome difficulties in providing attitude knowledge during transients, high slew rates (up to 40°/s), or periods of star camera occlusion. [3]

2. ISC VALIDATION APPROACH

A rigorous suite of ground and flight tests will accomplish technology validation. CSDL will conduct a series of analytical measurements, computer simulations, rate-table tests, star simulation tests, and night sky observatory tests to validate the concept on the ground. These tests will characterize the performance of the ISC over varying camera update rates, angular slew rates, and temperature ranges. The ISC validation objectives are shown in Table 1.

Table 1 – Validation Objectives

Objective	Where Tested	Metric
Accuracy (1-sigma) in each axis with slewing < 40 deg/s	Ground & Flight	0.1 deg
Self-initialization	Ground & Flight	< 10 min over 90% of sky
Power	Ground & Flight	< 4.5 W
Mass	Ground	< 3 kg
Space Qualified Component	Ground & Flight	Operates in typical Earth orbit environment

Flight vs. Ground Allocation

Flight validation of the ISC will demonstrate to potential users that the ISC is a mature, space-qualified technology (Technology Readiness Level 8). Prior to this flight, the ISC has been subjected to an exhaustive ground validation process, intended to maximize the chance of on-orbit success. To the extent possible, the allocation of validation tests is biased toward ground testing for better visibility and control of the system and assurance of test completion.

During flight, specific on-orbit tests will verify, for the first time in a space environment, performance of the MEMS gyros; Angle Random Walk (ARW), scale factor, and bias stability. The ISC's predicted camera performance (dim star limit, chromatic and astronomical aberration, sun and moon keep out angles) will also be validated in the relevant space environment. The integrated performance of the MEMS gyros and APS star imager will be demonstrated under various 3-axis maneuver profiles.

3. ISC GROUND VALIDATION

OverallRoadmap

Having discussed overall ground validation for the ISC program, a more detailed description of the process of ground validation follows. The validation flow was structured along the natural functional lines of the overall system, with subsystems validated separately and the flow gradually building up to validation of the fully integrated ISC system. A top-level overview of the entire process is provided in Figure 3.

The ISC system-level validation encompasses many potentially labor-intensive steps that would traditionally be required in the integration of a suite of separate attitude determination sensors onto a spacecraft. The ISC system validation process shown in the figure is inherently complex because the ISC integrates several sensors. This complexity is a burden shifted from the spacecraft integrators to the instrument designers, to the benefit of both parties. On one hand, the team performing sensor integration with the spacecraft sees reductions in cost, risk and schedule because integration is greatly simplified. On the other hand, the instrument designers, with their detailed knowledge of the internal workings of each sensor, are best prepared to attack the complexity of blending different attitude measurements in an optimal fashion.

APS Camera Testing—The test campaign broke down into four phases, each using a different test setup. Some preliminary tests were conducted on the bench top with the EM camera. Next, the bulk of camera testing was performed with the flight unit CGA in the thermal vacuum chamber with the star simulator shining in through a window. Following this, some tests were performed on the rate table, again using the star simulator. Finally, night sky tests provided the ideal environment to confirm parameters that were previously measured in the lab.

Camera Analytical Models—Models of increasing levels of fidelity were developed to understand the relationships between key design parameters and their effect on overall performance of the camera. The models provided insight into the effect of various operating conditions on the attitude error statistics of the camera, which are ultimately the only

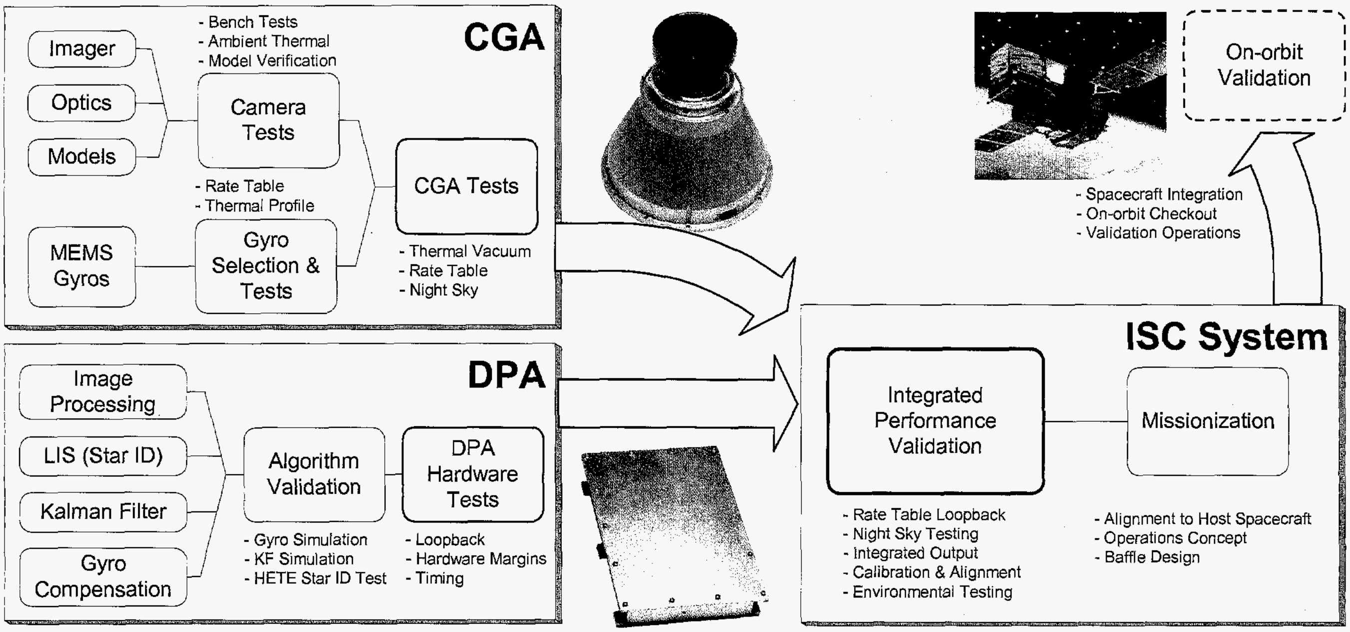


Figure 3 – ISC Ground Validation Process Overview

numbers that matter in the camera's contribution to overall instrument performance.

Camera Solar Exposure—There was concern that prolonged exposure to the sun while the camera was operating might damage the imager. The EM camera was taken outdoors and exposed to the June sun on a very clear day, under ambient pressure conditions. To detect any damage to the imager, dark frame and sensitivity tests were performed before and after exposure.

Camera Ambient Pressure Focus—With the flight camera assembly complete, preliminary focus was established iteratively by using a set of plastic lens shims. The focus test also provided a measurement of the smallest spot size achievable with the optics.

Camera Noise Equivalent Angle (NEA)—The single-star NEA performance was measured in the TV chamber, using the star simulator, and compared to the camera analytical models.

Camera Chromatic Aberration—The chromatic aberration test was performed with the star simulator and TV chamber setup. Kodak Wratten color filters were placed in front of the chamber window, and changes in star image spot size and location were monitored.

Camera Vacuum Focus—The vacuum focus was measured using the same method as in the ambient pressure focus test, but this time in the TV chamber with the star simulator shining through the chamber window. The temperature of the TV chamber was varied to verify that focus was constant over temperature, using a temperature range slightly wider than the nominal operating range.

CGA Thermal Vacuum—The thermal response of the CGA hardware was tested in the TV chamber over a variety of temperature ranges, operating or not, in order to obtain sufficient data to validate the analytic thermal model of the instrument. The temperature was controlled at the base plate of the instrument, and the chamber walls remained at ambient temperature.

CGA Thermal Survival—Using the same thermal vacuum setup, the un-powered CGA was exposed to temperature extremes under vacuum. Following several hours of exposure, the CGA temperature was brought back into its operational range, and a functional test was performed to confirm survival.

Camera Dark Frame—The approach used to compensate raw images for dark current effects was constrained by DPA memory, which could only store a single dark frame. Dark frames were collected during thermal vacuum testing over the entire operating range of the camera. A dark frame compensation method was devised to scale this single "master" dark frame to any desired temperature, using a temperature lookup table.

Camera Rate Tracking—This test verified performance of the camera against the tracking limit specification of 0.25 deg/s. The test was performed with a single moving star, with results matched against the analytical models. A more comprehensive test of tracking performance was conducted in further night sky tests.

Camera Calibration Parameters—The camera calibration consists of five parameters: focal length, two components of the optical center, and two radial lens distortion coefficients. These five parameters are used to translate the pixel coordinates of a star image into a body-fixed unit vector in the direction of the observed star. The quality of the calibration affects not only the accuracy of the final computed attitude, but more importantly the performance of the star identification algorithm.

Camera Sensitivity—The first night sky test using the flight CGA unit provided proof that the sensitivity matched the predictions of the analytical models. The temperature dependence of sensitivity was also tested, by heating the CGA base plate with a hair dryer and monitoring performance as a function of imager temperature.

MEMS Gyro Testing—A complete three-axis gyro board was assembled in a test fixture and mounted on a two-axis rate table with thermal control. The three-axis gyro board was run for several thermal cycles over the entire CGA temperature range while subjected to various rates.

DPA Testing

Thorough hardware and software tests of the DPA were required before integrated tests with the CGA. This included testing of the processor board, PSE (Power Supply Electonics), a DC/DC converter, and the embedded flight software.

Processor Testing—Hardware testing was conducted for many processor functions. Most notable was running the ERC-32 at 4MHz, which is much lower than its capability. This allowed for significant power reduction and yet easily met the ISC throughput requirements.

Algorithm Testing — Traditionally, attitude determination algorithms are separately developed, integrated and tested by the spacecraft developers integrating the sensor suite. As an integrated attitude sensor, the ISC will significantly unburden these spacecraft developers by having all the algorithms pre-integrated and tested within the instrument.

Integrated Testing

Integrated testing includes bench testing, rate table testing and night sky testing.

Bench Testing — This critical portion of the test program allowed the development of the necessary GSE and software ground tools to provide visibility into the inner workings of the ISC. Bench testing was first performed on the breadboard system, and later on the flight system prior to packaging into the housing.

Rate Testing — Unlike many other attitude systems, the three-axis rate output of ISC is pre-compensated over temperature for bias, scale factor and axis misalignment. A two-axis rate table with thermal control allowed each gyro to be accurately characterized over a range of rates and temperatures.

Night Sky Testing — Testing performed under the night sky, with the fully integrated ISC, went considerably beyond the CGA-only night sky tests described under camera testing. The purpose of integrated night sky testing was to prove that the sensors and algorithms worked together and produced the required attitude determination performance under a variety of operating conditions. A more comprehensive night sky test was conducted specifically to probe the edges of the operating envelope. The CGA was placed inside a thermal enclosure and driven to its temperature extremes while operating in order to characterize its degradation in performance as temperature limits are exceeded. Other tests were also performed, including rate tracking to quantify the rate limit on a real star field, and final tuning of the Kalman filter.

Environmental Testing

For space qualification, the ISC will be subjected to a full complement of environmental tests. This includes ten cycles of GEVS-specified (General Environmental Verification Specification) thermal vacuum tests for both the DPA and CGA. During thermal vacuum testing only, a star simulator will be used to exercise the camera through a window in the chamber. For vibration testing, a low-level sine vibration sweep of each axis will be conducted to verify predicted resonances. Random vibration and shock tests will be conducted in each axis to proto-flight levels for Ariane 5. While the ISC is designed to be immune to spacecraft level EMI interference, a full quota of MIL-STD-461 EMI/EMC tests will be conducted, in addition to EMC compatibility testing on the host spacecraft.

4. THE AUTONOMOUS SCIENCECRAFT EXPERIMENT

While the ISC experiment is being readied for its flight at this writing another ST6 experiment is coming to its conclusion after a year of successful space testing.

The Autonomous Sciencecraft Experiment is currently flying onboard the New Millennium Program Earth Observing One (EO1) spacecraft. The ASE software enables the spacecraft to autonomously detect and respond to science events occurring on the Earth. The package includes software systems that perform science data analysis, deliberative planning, and run-time robust execution.

ASE has the following full success criteria:
1. Five times autonomously plan, schedule and execute a payload data downlink.
2. Five times autonomously schedule and execute onboard a payload data collect of the prescribed area.
3. Five times edit the content of the downlink of payload data to retain only data of interest.
4. Five times perform science analysis of the payload data to select and image a target with observed change.
5. Reconstruct on the ground all flight mission planning and analysis.

The minimum success criteria have the same five objectives but require only successful planning and scheduling without the execution.

This software demonstrates several integrated autonomy technologies to enable autonomous science. Several algorithms are used to analyze remote sensing imagery onboard in order to detect the occurrence of science events. These algorithms are used to downlink science data only on change, and detect features of scientific interest such as volcanic eruptions, flooding, ice breakup, and presence of cloud cover. The results of these onboard science algorithms are inputs to onboard planning software that then modify the spacecraft observation plan to capture high-value science events. This new observation plan is then be executed by a robust goal and task oriented execution system, able to adjust the plan to succeed despite run-time anomalies and uncertainties. Together these technologies enable autonomous goal-directed exploration and data acquisition to maximize science return.

The ASE onboard flight software includes several autonomy software components:

- Onboard science algorithms that analyze the image data to detect "trigger" conditions such as science events, "interesting" features, changes relative to previous observations, and cloud detection for onboard image masking
- Robust execution management software using the Spacecraft Command Language (SCL) [**Error! Reference source not found.**] package to enable event-driven processing and low-level autonomy
- The Continuous Activity Scheduling Planning Execution and Replanning (CASPER) [0] software that modifies the current spacecraft activity plan based on science observations in the previous orbit cycles

The onboard science algorithms analyze the images to extract static features and detect changes relative to previous observations. Several algorithms have already been demonstrated on EO-1 Hyperion data to automatically identify regions of interest including land, ice, snow, water, and thermally hot areas. Repeat imagery using these algorithms can detect regions of change (such as flooding and ice melt) as well as regions of activity (such as lava flows). We have been using these algorithms onboard to enable retargeting and search, e.g., retargeting the instrument on a subsequent orbit cycle to identify and capture the full extent of a flood. Although the ASE software is running on the Earth observing spacecraft EO-1, the long term goal is to use this technology on future interplanetary space missions. For these missions, onboard science analysis will enable data be captured at the finest time-scales without overwhelming onboard memory or downlink capacities by varying the data collection rate on the fly.

The CASPER planning software generates a mission operations plan from goals provided by the onboard science analysis module. The model-based planning algorithms will enable rapid response to a wide range of operations scenarios based on a deep model of spacecraft constraints, including faster recovery from spacecraft anomalies. The onboard planner accepts as inputs the science and engineering goals and ensures high-level goal-oriented behavior.

The robust execution system (SCL) accepts the CASPER-derived plan as an input and expands the plan into low-level spacecraft commands. SCL monitors the execution of the plan and has the flexibility and knowledge to perform event-driven commanding to enable local improvements in execution as well as local responses to anomalies. processor.

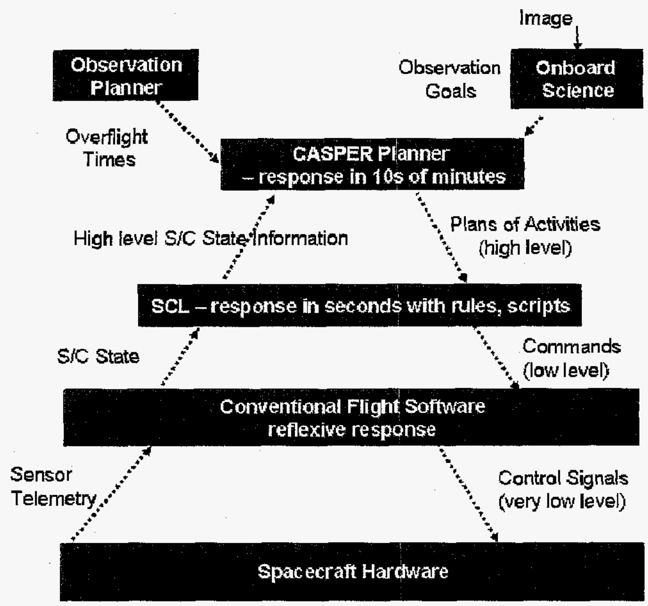


Figure 4. Autonomy Software Architecture

5. ASE AUTONOMY SOFTWARE ARCHITECTURE

The autonomy software on EO-1 is organized into a traditional three-layer architecture [8] (See Figure 4.). At the highest level of abstraction, the Continuous Activity Scheduling Planning Execution and Replanning (CASPER) software is responsible for mission planning functions. CASPER schedules science activities while respecting spacecraft operations and resource constraints. The duration of the planning process is on the order of tens of minutes. CASPER scheduled activities are inputs to the Spacecraft Command Language (SCL) system, which generates the detailed sequence commands corresponding to CASPER scheduled activities. SCL operates on the several second timescale. Below SCL, the EO-1 flight software is responsible for lower level control of the spacecraft and also operates a full layer of independent fault protection. The interface from SCL to the EO-1 flight software is at the same level as ground generated command sequences. The science analysis software is scheduled by CASPER and executed by SCL in a batch mode. The results from the science analysis software result in new observation requests presented to the CASPER system for integration in the mission plan.

This layered architecture was chosen for two principal reasons:

1. The layered architecture enables separation of responses based on timescale and most appropriate representation. The flight software level must implement control loops and fault protection and respond very rapidly and is thus directly coded in C. SCL must respond quickly (in seconds) and perform many procedural actions. Hence SCL uses as its core representation scripts, rules, and database records. CASPER must reason about longer term operations, state, and resource constraints. Because of its time latency, it can afford to use a mostly declarative artificial intelligence planner/scheduler representation.
2. The layered architecture enables redundant implementation of critical functions – most notable spacecraft safety constraint checking. In the design of our spacecraft agent model, we implemented spacecraft safety constraints in all levels where feasible.

Each of the software modules operates at a separate VxWorks operating system priority. The tasks are shown below in Table 2 in decreasing priority. The ASE to flight software bridge is the task responsible for reading the real-time flight software telemetry stream, extracting pertinent data, and making it accessible to the remainder of the ASE software. The Band Stripping task reads the science data from the onboard solid state recorder and extracts a small portion of the science data (12 bands of Hyperion data) to RAM. The science analysis software then operates on the extracted data to detect science events.

It is worth noting that our agent architecture is designed to scale to multiple agents. Agents communicate at either the planner level (via goals) or the execution level (to coordinate execution).

Table 2. EO-1 Software Tasks in Decreasing Task Priority (e.g. upper tasks have highest priority for CPU).

Set of Tasks	Rationale for Priority
EO-1 Flight Software	Required for processor hardware safety
ASE to FSW Bridge	Required to keep up with telemetry stream
Band Stripping	Utilizes processor hardware while running
SCL	Lowest level autonomy, closes tightest loops
CASPER	Responds in tens of minutes timescale
Science Analysis	Batch process without hard deadlines

We now describe each of the components of our architecture in further detail.

6. ASE ONBOARD MISSION PLANNING

In order for the spacecraft to respond autonomously to a science event, it must be able to independently perform the mission planning function. This requires software that can model all spacecraft and mission constraints. The CASPER [0] software performs this function for ASE. CASPER represents the operations constraints in a general modeling language and reasons about these constraints to generate new operations plans that respect spacecraft and mission constraints and resources. CASPER uses a local search approach [0] to develop operations plans.

Because onboard computing resources are limited, CASPER must be very efficient in generating plans. While a typical desktop or laptop PC may have 2000-3000 MIPS performance, 5-20 MIPS is more typical onboard a spacecraft. In the case of EO-1, the Mongoose V CPU has approximately 8 MIPS. Of the three software packages, CASPER is by far the most computationally intensive. For that reason, our optimization efforts were focused on CASPER. Careful engineering and modeling were required to enable CASPER to build a plan in tens of minutes on the relatively slow CPU.

CASPER is responsible for long-term mission planning in response to both science goals derived onboard as well as anomalies. In this role, CASPER must plan and schedule activities to achieve science and engineering goals while respecting resource and other spacecraft operations constraints. For example, when acquiring an initial image, a volcanic event is detected. This event may warrant a high priority request for a subsequent image of the target to study the evolving phenomena. In this case, CASPER will modify the operations plan to include the necessary activities to re-image. This may include determining the next over flight opportunity, ensuring that the spacecraft is pointed appropriately, that sufficient power and data storage are available, that appropriate calibration images are acquired, and that the instrument is properly prepared for the data acquisition.

In the context of ASE, CASPER reasons about the majority of spacecraft operations constraints directly in its modeling language. However, there are a few notable exceptions. First, the over flight constraints are calculated using ground-based orbit analysis tools. The over flight opportunities and pointing required for all targets of interest are uploaded as a table and utilized by CASPER to plan. Second, the ground operations team initially performs management of the momentum of the reaction wheels for the EO-1 spacecraft. This is because of the complexity of the momentum management process caused by the EO-1 configuration of three reaction wheels rather than four.

7. ASE ONBOARD ROBUST EXECUTION

ASE uses the Spacecraft Command Language (SCL) to provide robust execution. SCL is a software package that integrates procedural programming with a real-time, forward-chaining, rule-based system. A publish/subscribe software bus allows the distribution of notification and request messages to integrate SCL with other onboard software. This design enables both loose or tight coupling between SCL and other flight software as appropriate.

The SCL "smart" executive supports the command and control function. Users can define scripts in an English-like manner. Compiled on the ground, those scripts can be dynamically loaded onboard and executed at an absolute or relative time. Ground-based absolute time script scheduling is equivalent to the traditional procedural approach to spacecraft operations based on time. SCL scripts are planned and scheduled by the CASPER onboard planner. The science analysis algorithms and SCL work in a cooperative manner to generate new goals for CASPER. These goals are sent as messages on the software bus.

Many aspects of autonomy are implemented in SCL. For example, SCL implements many constraint checks that are redundant with those in the EO-1 fault protection software. Before SCL sends each command to the EO-1 command processor, it undergoes a series of constraint checks to ensure that it is a valid command. Any pre-requisite states required by the command are checked (such as the communications system being in the correct mode to accept a command). SCL will also verify that there is sufficient power so that the command does not trigger a low bus voltage condition and that there is sufficient energy in the battery. Using SCL to check these constraints (while included in the CASPER model) provides an additional level of safety to the autonomy flight software.

8. Conclusions

The significance of the ISC and ASE technologies is in making the space missions less dependent on operators on the ground and shifting the decision making to the spacecraft itself. ISC is a bolt on device that integrates several pieces of hardware currently procured separately and tied with custom algorithms and software. This kind of system will be able to be entirely substituted by the ISC instrument. The ASE may also help reduce ground operation costs, especially as calculated with relation to important science returned by the mission.

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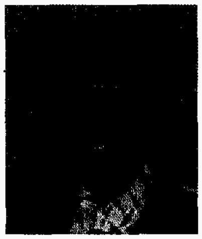
11. BIOGRAPHY



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